PROGRESS OF THE US LASER DEVELOPMENT FOR THE LASER INTERFEROMETER SPACE ANTENNA (LISA) PROGRAM

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ABSTRACT

NASA Goddard Space Flight Center (GSFC) has been actively developing the laser transmitter for the Laser Interferometer Space Antenna (LISA) program since the late 2017. We have delivered a prototype laser transmitter to the LISA program for performance evaluation in 2021. We continued to further develop the LISA laser with a goal of advancing the technology readiness level (TRL) of the laser to 6 by the end of 2023. In this paper, we report on the progress we made on the laser development for the LISA program.

***Index Terms*—** space instrument, laser interferometer, gravitational wave observatory, solid state lasers, fiber amplifier, ultra-stable laser, space laser

1. INTRODUCTION AND LASER REQUIREMENTS

A highly stable and robust laser design is a key subsystem to the LISA observatory. LISA was selected to be the European Space Agency's (ESA) third large-class mission and will be the first space-based gravitational wave (GW) observatory to address the science theme of the Gravitational Universe. The LISA observatory consists of three spacecraft separated by 2.5 million km in a triangular formation, following Earth in its orbit around the Sun. Launch is expected in 2037 [1].

LISA will use a heterodyne laser interferometer to measure picometer-level length variation between the spacecraft at 1000-sec timescales. Each spacecraft contains two drag-free test masses, to which the spacecraft follows in drag-free mode. The length variation between the free-floating test masses in each spacecraft is monitored precisely to observe the passage of the GWs, which are generated, for example, by mergers of super-massive black holes. NASA continues to collaborate with ESA, with the laser transmitter being one of the potential contributions to the LISA mission.

The LISA observatory consists of three spacecraft (S/C) as shown schematically in *Figure 1*. Each S/C carries one laser system (LS). The LS is made up of two laser assemblies (LA) and each LA has two laser heads (LH) as shown in Figure 1. Only one of the two LHs in an LA will be on at any one time for the mission. The other LH is a cold spare to meet the mission lifetime. Each LH includes a laser optical module (LOM) and a laser electronics module (LEM). The LH enables the interferometric sources for the LISA mission.

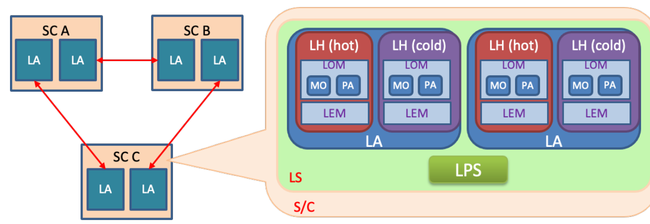

Figure 1. LISA Observatory.

The GSFC baseline LOM takes on the master oscillator power amplifier (MOPA) architecture that comprises a low-power, low-noise master oscillator (MO) followed by a power amplifier (PA) stage with a nominal output power of ~2 W throughout the mission. Our effort includes advancing the laser from the breadboard concept to space qualified demonstrator in preparation for the LISA mission. In the following sections, we describe the progress on the laser development effort for the LISA mission and plans to demonstrate a TRL 6 (Technology Readiness Level [2]) LISA laser demonstrator system by 2024.

Top level requirements for the LISA LH are [3]

- Dimensions 330 × 330 × 250 mm^3
- Mass 12kg
- LH dissipated power <75W (TBR)
- LH operating temperature 20±5°C (TBR)
- LH non-operating temperature -20°C to +40°C (TBR)
- LOM Output Power >2W on optical bench (OB) at end of life (EoL)
- Wavelength 1064.50, -0.05/+0.10 nm
- Polarization extinction ratio (PER) >20dB (TBC)
- Lifetime >16 years
  - 6 years - 1 year for on-ground integration and testing, plus 5 years (TBC) of storage
  - 1.5 years TBC OFF state in operational environment (cruise phase)
  - 5 (TBC) years continuous operation in nominal science mode (nominal mission lifetime)
  - 11 (Goal) years continuous operation in nominal science mode (extended mission lifetime)

The wavelength selected for the precision interferometer is 1064 nm due to availability of high-quality bulk and fiber optic components with extensive flight heritage and the traditional low-noise Nd:YAG laser source implemented as an NPRO (non-planar ring oscillator) [4]. The available laser power sets a shot noise limit on the detection sensitivity of the gravitational waves at the high frequency end of the

detection band (>~10 mHz). In addition to the standard requirements for mass, power, radiation hardness, and other requirements as a space laser, the most challenging requirements are set by the low frequency noise (that requires active stabilization using a high finesse optical cavity), by the low intensity noise (that requires active stabilization at low Fourier frequency and shot-noise-limited performance at high Fourier frequency), and by the long lifetime (~16 years including integration, test, and cruise phases). The GSFC LISA laser has been designed to satisfy these unique requirements.

2. BASELINE LASER ARCHITECTURE

Our MOPA laser design is shown schematically in Figure 2.

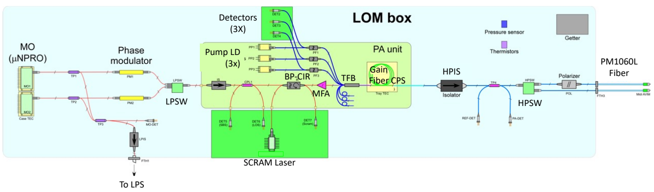

Figure 2. Schematic of the GSFC LISA laser.

There are two micro-Non-Planar Ring Oscillator (μ-NPROs) MO's and two phase modulators (PM) to provide full redundancy for the mission. These are connected to a 2x1 low power optical switch (LPSW) that provides selectivity of the MO and PM for the PA. Internal to the μNPRO, there are two 808 nm pump diodes, polarization combined to pump an NPRO crystal, both 808 nm pump diodes are nominally operating at >50% derating to meet the operational requirement. The output of the PA is followed by an output high power optical isolator. The PA subassembly consists of a radiation hardened ytterbium polarization maintaining gain fiber pumped by a single 976 nm pump diode with 2 full redundant diodes via a tapered fiber bundle (TFB) in the subassembly. The output of the MOPA is nominally 2 Watts average power to meet systems requirements. One of the most challenging requirements of the LISA laser is the long lifetime requirement, including on-ground testing, a 16-year lifetime is placed on the laser system. Full redundancy and significant derating of critical components, especially the 808 nm pump diodes for the μNPROs and 976 nm pump diodes for the power amplifier are used to meet the reliability requirement.

The main optical output of the MOPA laser is a linearly polarized, continuous wave (CW) laser beam. This beam is sent to the optical bench (OB) of the instrument via a PM1060L polarization maintaining optical fiber (PMF). In a baseline operating mode, one of the 6 active lasers is frequency-locked to a high finesse cavity as a master laser for the rest of the system, while the other five active lasers are offset phase-locked to the master laser as transponder lasers, acting as an amplifying mirror at far spacecraft. The laser is frequency-locked to an optical reference cavity that is the main function of the Laser Prestabilization System (LPS). In each of the MO path inside the LH, a tap coupler is used to provide input to the LPS for frequency locking. The LOM also includes a high power optical switch (HPSW) after the high power output isolator (HPIS) for turning the laser output either to the distant S/C for normal operation or to deep space during the S/C acquisition. This allows the laser to remain in a constant thermal state throughout the mission life.

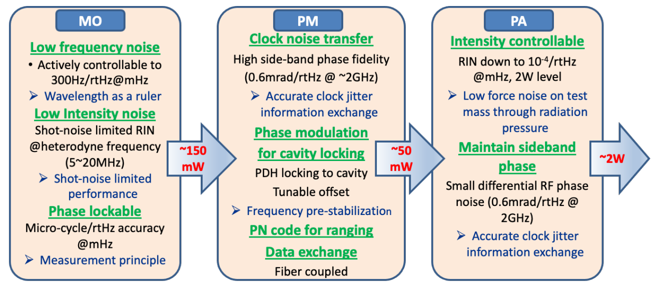

Figure 3. Functions of subsystems – MO, PM, and PA for the LISA laser.

The functionalities and key features of key subsystems within the LOM and nominal power levels are shown in *Figure 3* [5,6].

The MOPA laser consists of a MO laser source (the 'seed'), a PA for power scaling, and a PM for imprinting clock noise transfer, ranging, and data information on the main laser carrier. Each MO has a PM, which is an electro-optical phase modulator (EOM) within the optical path to transmit reference clock information between spacecraft using the phase-modulation sideband at ~GHz. Without the clock noise transfer (exchange), the small gravitational wave signal would be buried in the clock noise on the three spacecraft. Practically, GHz-level phase-modulation can be added only by a waveguide-based EOM, which is known to handle less than ~200 mW of optical power.

The LEM interfaces with the LOM and the payload computer as shown schematically in *Figure 4*: (a) LH drive electronics (LHDE) provides the main control of the laser system, e.g., coarse setting of the laser power and frequency, as well as health monitoring; (b) LH frequency control electronics (LHFC) processes the control signal for coarse frequency setting signal and the external/pre-stabilization frequency change commands; (c) LH laser modulation control electronics (LHMC) accepts modulation waveforms from the frequency distribution system (FDS), and applies them with appropriate modulation index (amplitude) to the laser light. The LHMC may also accept phase modulation required for the Pound-Drever-Hall (PDH) locking to LPS, depending on the frequency noise reduction scheme chosen; (d) LH Power Control electronics (LHPC) is responsible for the relative intensity noise (RIN) suppression at ~10-kHz bandwidth, by acting on the PA.

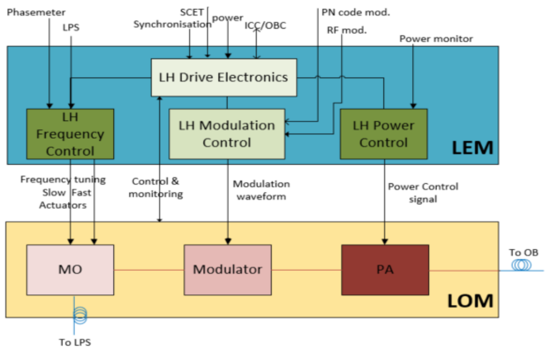

Figure 4. Interfaces between LOM and LEM within LH and payload and on-board computer (ICC/OBC) to receive S/C Event Time (SCET) and RF and pseudo-noise (PN) modulation signals for the laser.

3. TRL4 LASER PERFORMANCE

In May 2021, we delivered a TRL4 packaged LOM (see Figure 5), a commercial off-the-shelf (COTS) LEM and a RIN stabilization ground support equipment (GSE) to the Centre Suisse d'Electronique et de Microtechnique (CSEM), a laser metrology center for ESA for performance evaluation.

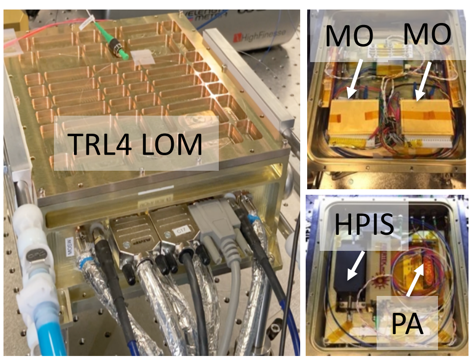

Figure 5. TRL4 LOM.

The TRL4 laser performance is summarized in Figure 6. In Figure 6(a), the free-run frequency noise of the laser showed a very small noise and drift, meeting the LISA requirement. In the kHz to MHz frequency range, the high voltage (HV) amplifier that was used to drive the piezo transducer (PZT) that is bonded to the NPRO crystal for frequency tuning contributed to the noise above the LISA requirement. We have successfully improved the µ-NPRO laser to operate without the use of HV amplifier thus eliminating the noise as shown.

In Figure 6(b), the stabilized laser met the stringent 30Hz/rtHz requirement. Again, the HV amplifier used in the TRL4 laser for the PZT violated the LISA requirement at high frequency. In addition, the servo bump from the GSE high finesse (~400,000) optical cavity was evident. These have been eliminated in the TRL6 laser development. In Figure 6(c), the differential phase noise of the LOM was measured. The area in the 1-10 mHz frequency range where the data violated the LISA laser requirement is thought to be due to GSE test station noise. This will be verified in future improved test station.

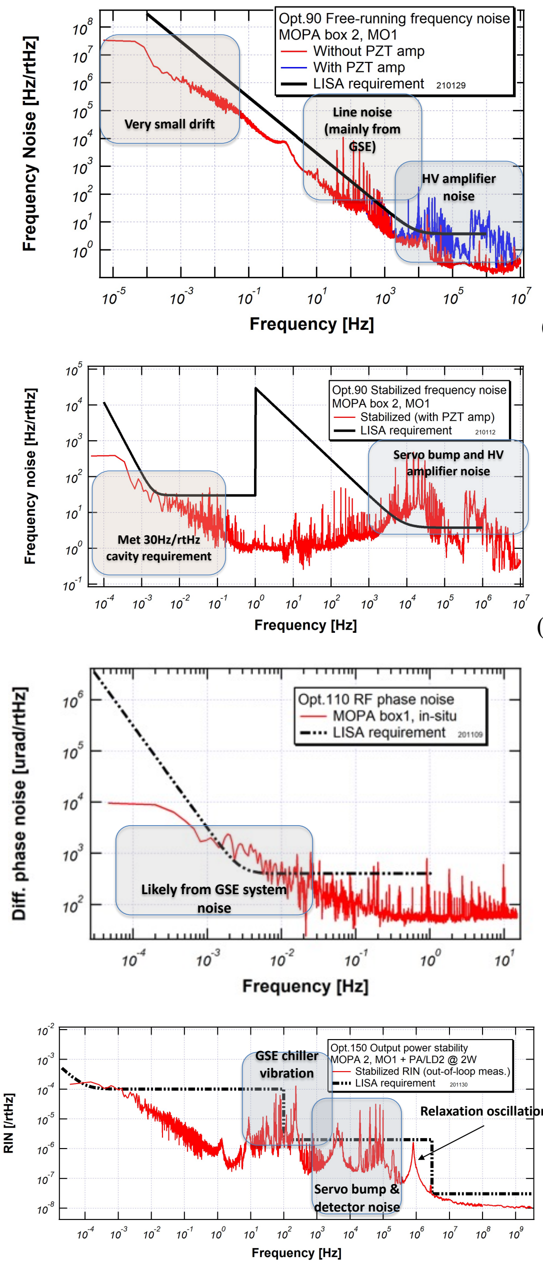

Figure 6. Performance of the delivered TRL4 LOM: (a) Free-run frequency noise; (b) Stabilized frequency noise; (c) RF (differential) phase noise and (d) RIN. The LISA laser requirement in each case is shown as either black solid or dashed line in respective graphs.

We are actively improving the in-situ GSE measurement station to minimize the system noise. The RIN performance is shown in Figure 6(d). Again, as in previous requirements, the GSE system noise showed up in the data. The laser was stabilized with the GSE "mock-up bench" setup operating in air and the two meeting the important requirements at low

frequency and high frequency. A noise eater system was employed for the μNPRO. Future GSE upgrade include having the mock-up bench in vacuum that will improve performance in the low to mid frequency range.

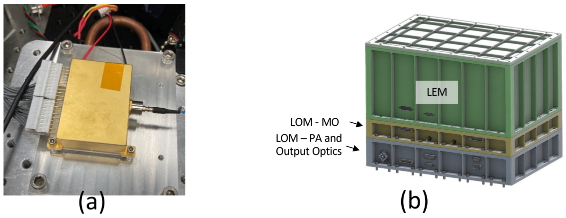

Figure 7. TRL6 (a) μNPRO and (b) LH designs.

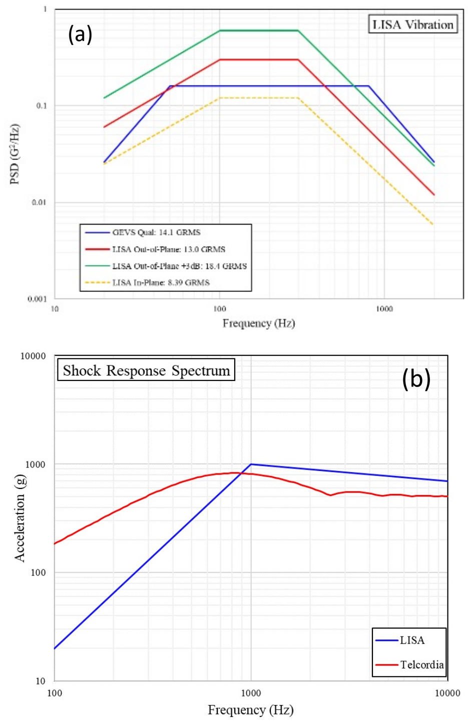

Figure 8. (a) Random vibration profiles for LISA and GEVS; (b) Shock profiles for LISA and Telcordia.

4. TRL6 LASER DESIGN

The TRL4 packaged LOM is designed to be a two-sided enclosure where an optical bench in the middle of the enclosure serves as the common mounting surface for either side, as seen in Figure 5. In this approach, the two MO's, PM's and the LPSW as shown in Figure 2 are assembled on one side of the box and the PA, HPIS and HPSW are on the other side. We have done extensive finite element analysis (FEA) on this enclosure design based on the LISA environmental requirements. The FEA results showed potentially damaging amplification of the random shock and vibration levels on critical components on the PA. We, therefore, updated our TRL6 LOM design as well as the LEM enclosure to that shown in Figure 7(b). Initial FEA shows promise, and we are in the process of finalizing this TRL6 design and proceed to build this demonstrator for full environmental testing. In parallel, we have updated and improved the MO design [7] as seen in Figure 7 (a). The LISA random shock and vibration requirements [3] are shown in Figure 8 (a) and plotted against the NASA General Environmental Verification Standard (GEVS) [8]. Also shown in Figure 8 (b) is the shock profile for LISA plotted Telcordia qualification level for fiber optic components [9]. Four TRL6 μ-NPRO MO have been built and we have performed random vibration tests to the GEVS level and gamma radiation tests with accumulated dosage of 40 krad. Performance of the μ-NPRO remained the same. Initial temperature cycling tests are in progress.

5. CONCLUSIONS

GSFC has been developing the laser transmitter for the LISA mission since late 2017. We are working toward delivering a TRL6 LH and LPS to ESA for evaluation in 2023. The current schedule for the TRL6 laser development is as follows. A TRL6 LOM will be demonstrated by 3rd quarter 2022, follows by a TRL6 LEM by 3rd quarter 2023. The TRL6 LH will be demonstrated and fully environmentally tested by 4th quarter 2023 and deliver to ESA for extensive testing by early 2024. A TRL6 LPS will also be delivered with the TRL6 LH for full system performance evaluation. This laser, once launched, will be one of the most stable lasers ever flown in space to realize the LISA GW observatory as noted by the recently released 2020 Astrophysics decadal survey [10].

6. ACKNOWLEDGEMENT

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